

# Improved high-speed de-excitation system for brushless synchronous machines tested on a 20 MVA hydro-generator.

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**Abstract:** Synchronous machines with brushless excitation have the disadvantage that the field winding is not accessible for the de-excitation of the machine. This means that, despite the proper operation of the protection system, the slow de-excitation time constant may produce severe damage in the event of an internal short circuit. A high-speed de-excitation system for these machines was developed, and this study presents the continuation of a previously published study. This study presents the design by computer simulation and the results of the first commissioning of this de-excitation system in a commercial 20 MVA hydro-generator. The de-excitation is achieved by inserting resistance in the field circuit, obtaining a dynamic response similar to that achieved in machines with static excitation. In this case, a non-linear discharge resistor was used, making the dynamic response even better.

## Nomenclature

$R_f$	resistance of the rotor winding
$L_f$	inductance of the rotor winding
$M_f$	rotor stator coupling
$L_d$	direct axis synchronous inductance
$T_d'$	rotor load time constant
$T_{d0}'$	rotor unload time constant
$R_d$	discharge resistor of the main generator
$I_{f\_exc}$	excitation current of the exciter
$I_f$	rotor current of the main generator
$U_f$	rotor voltage of the main generator
$I_r$	current discharge resistor
$R_d$	discharge resistor of the main generator
$R_{d\_exc}$	discharge resistor of the exciter
$X_d$	direct axis synchronous reactance
$X_d'$	direct axis transient synchronous reactance
$X_d''$	direct axis subtransient synchronous reactance
$X_q$	quadrature axis synchronous reactance
$X_q''$	quadrature axis subtransient synchronous reactance
$T_d'$	direct axis transient time constant
$T_d''$	direct axis subtransient time constant
$T_q''$	quadrature axis subtransient time constant

## 1 Introduction

If one does a search for ‘monitoring’ or ‘protection’ of electrical machines in international technical publications, one can find a great number of really interesting papers, but in most cases tests only involve small machines under laboratory conditions. These works are important contributions to knowledge, even if they are only validated in the laboratory. Only a few of these monitoring and protection systems have been fruitfully tested in large machines under real conditions, in which unexpected events could be present, such as noise, electromagnetic interference, high temperatures etc.

This paper presents the results of the commissioning of a novel high speed de excitation system for brushless synchronous machines, as well as the design by computer simulation. The new system was tested in a real 20 MVA hydro generator in a power

plant, having previously been developed and tested in a 5 kVA laboratory machine. In this 20 MVA generator, non linear discharge resistors are used, which improve the transient behaviour compared with linear resistors. This generator has been in satisfactory operation with this new de excitation system for one year.

Faults in synchronous machines could eventually pose a risk to power plant facilities and staff. For this reason, they are equipped with protection relays to minimise the damage in case of abnormal operation or default, such as overload, internal or external short circuit, loss of excitation etc. Minimum requirement specifications ensure adequate protection in the event of any type of default in any part of the generator, such as the stator winding, the rotor winding, the rotating diodes or the exciter [1].

Modelling synchronous machines and their excitation systems under an internal fault condition is not straightforward [2 6]; however, it is well known that it is necessary to achieve a rapid de excitation of the synchronous machine to limit possible damage [7, 8]. This requires elimination of the voltage source feeding the fault as soon as possible, but this cannot be done simply by opening the generator breaker, as the generator may be supplying part of the fault current itself. Hence, the suppression of the field current, and consequently the air gap flux, must be forced [9]. In synchronous machines with static excitation systems it is common practice to insert a discharge resistor into the rotor circuit to dissipate the stored energy in the field winding. On the other hand, in conventional brushless synchronous machines, as the field winding is not accessible, the stored energy can only be dissipated in the field winding resistance and therefore the de excitation time is considerably longer.

The slow de excitation time constant of conventional brushless synchronous machines, despite the proper operation of the protection system, may produce severe damage in the event of an internal short circuit. To reduce the damage, and to improve transient behaviour, a high speed de excitation system, based on the insertion of a rotating discharge resistor in the field circuit, was previously presented [10, 11]. This system, named high speed brushless de excitation system (HSBDS), was developed and tested in a 5 kVA laboratory machine based on linear resistors. Logically, its performance for this machine should not be easily extrapolated to large generators directly, because of significant

constructive variations between the two types of machine, such as the enormous differences in the voltage, current and energy to be dissipated. Another important factor to take into consideration is the conditions in a real hydro power plant compared with the laboratory conditions where the first prototype was tested.

Compared with other methods for rapid de excitation of brushless machines [12–15], the HSBDS proposed in [10, 11] has the great advantage that it does not need any external control device. Rather, the insertion of the discharge resistor is achieved by a control circuit placed on the rotor itself, which actuates according to the voltage of rotating diodes.

Excitation systems and automatic voltage regulators are very active research topics, and important research has been carried out recently in hybrid excitation [16, 17], parameter identification [18], excitation structures [19], control strategies [20, 21] and power system stabilisers [22].

This paper is structured as follows: Section 2 summarises the operating principle of the HSBDS. Section 3 shows the results of the computer simulations used for the design of the HSBDS for a 20 MVA brushless hydro generator. Section 4 presents the results of the tests undertaken during the commissioning in the hydro power plant. Finally Section 5 concludes with a summary of the main contributions of the paper.

## 2 Brief theoretical description of the HSBDS

In this section, the main ideas are summarised to help one understand the rest of the paper. State of the art developments and the detailed operation principle of the de excitation system were described in [10].

The transient behaviour of the synchronous machine is represented by the transient time constant (1), which depends on the field winding impedance ( $R_f$ ,  $L_f$ ), the rotor stator coupling ( $M_f$ ) and the stator winding inductance ( $L_d$ ). The time constant under no load condition (2) only depends on the field winding impedance. In any case, both time constants are inversely proportional to the field winding resistance

$$T'_d = \frac{L_f}{R_f} \frac{(M_f^2/L_d)}{R_f} \quad (1)$$

$$T'_{d0} = \frac{L_f}{R_f} \quad (2)$$

The typical value of the time constant of a large brushless machine is in the range of 0.5 to 1 s for  $T'_d$  (1) and 5 to 9 s for  $T'_{d0}$  (2). In the event of a stator internal failure, the damage would be very severe, even if the electrical protection relays operated correctly. As the short circuit current supplied by the machine will last several seconds, it is essential that the system must quickly remove the rotor current ( $I_f$ ) to minimise damage to the stator.

The proposed de excitation (Fig. 1) system consists of a discharge resistor ( $R_d$ ), connected between the rotating diode bridge and the main machine field winding by a transistor switch. This transistor switch is controlled through the voltage measured at the diode bridge by a rotating control circuit mounted in the rotor, thus eliminating the need for an external signal, via either radio, slip rings or special transformers [12–15]. Hence, the generator protection system, the excitation system and the automatic voltage regulator scheme would remain the same as in a conventional brushless synchronous machine and the discharge resistor would only be automatically connected if field suppression were to be required.

During the normal operation (Fig. 1a) of the synchronous machine, a current ( $I_{f\_exc}$ ) flows through the exciter field winding, as shown in Fig. 1a. This induces an AC voltage in the armature windings of the exciter and current flows through them, feeding the main synchronous machine field winding with a field current ( $I_f$ ). Consequently, a positive voltage appears at the diode bridge and thus at the field winding ( $U_f$ ). The positive voltage in the

diode bridge makes the control circuit activate the transistor switch, hence the current flows mainly through it and only a small current flows through the discharge resistance because of the voltage drop across the transistor switch.

In the event of an electrical trip (Fig. 1b) in a brushless synchronous machine, only the exciter field winding current can be reduced quickly, as the rotor of the main machine is not accessible. By decreasing the current in the exciter field winding, the output voltage at the diode bridge drops. Then, a voltage will be induced in the field winding of the main machine with opposite to normal polarity, as it is highly inductive. Thus, the current through the winding would not change suddenly, nor would the magnetic flux. The reverse voltage induced in the field winding causes the voltage in the diode bridge to become slightly negative, and the control circuit will turn off the transistor switch, hence leading the field current to flow through the discharge resistor ( $R_d$ ), as shown in Fig. 1b.

This operating scheme reduces the de excitation time constant of the main synchronous machine significantly, by adding the discharge resistor in the circuit, as indicated in (3) and (4). The resulting transient response of the brushless machine is made comparable with that of a static excitation machine by dimensioning the discharge resistance adequately

$$T'_d = \frac{L_f}{R_f + R_d} \frac{(M_f^2/L_d)}{R_f + R_d} \quad (3)$$

$$T'_{d0} = \frac{L_f}{R_f + R_d} \quad (4)$$

Nevertheless, it is common to use non linear resistors [9] made of silicon carbide (SiC) or zinc oxide, to reduce the de excitation time and improve the answer in case of fault. The calculation for this kind of resistor is the same as for conventional linear resistors, taking into account the maximum value of voltage and the energy that has to be dissipated. Obviously, the response curve should have the most non linear performance possible, to improve the de excitation time.

SiC resistors have a longer use life than zinc oxide. However SiC resistors have remarkably less non linear characteristic (5). The coefficient  $C$  represents the voltage in the resistor when a current of 1 A flows through it. The coefficient  $\beta$  represents the non linearity; typically  $\beta$  has a value of 0.5 for SiC resistors and 0.05 for zinc oxide resistors

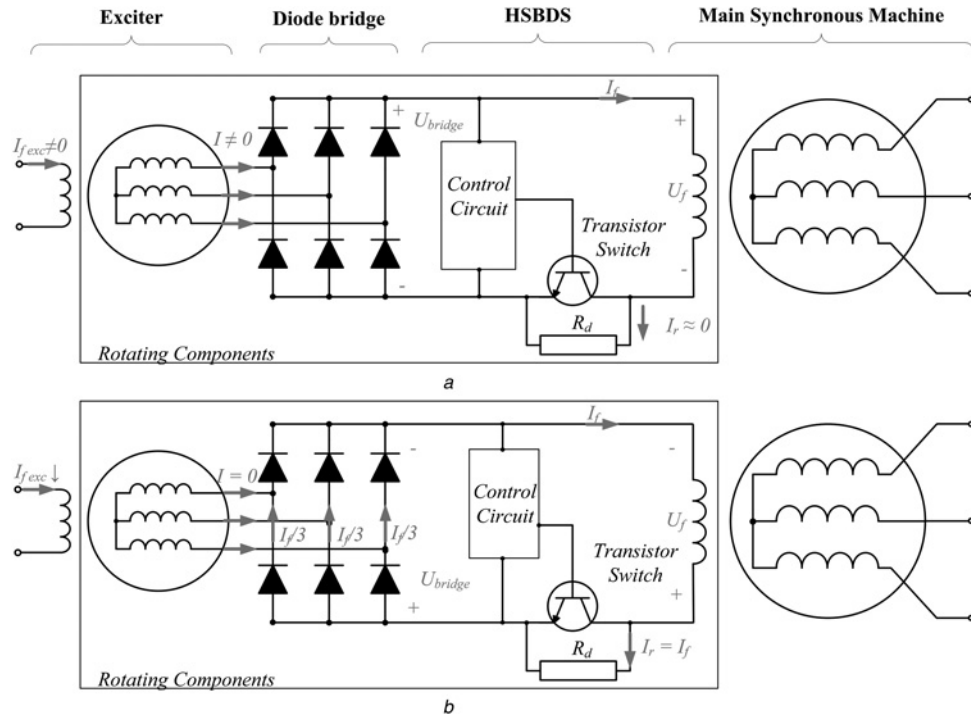
$$V = CI^\beta \quad (5)$$

## 3 Design of a HSBDS in a real hydro power plant of 20 MVA by computer simulations

One of the main concerns in the design of this de excitation system was the centrifugal force in the rotor, during normal operation and after a load rejection in rated overspeed conditions. As there was no experience with most of the components on this type of application, we decided to test all the components under similar rotating conditions to verify its correct operation. During these tests we found some components that do not work properly with this acceleration, so we had to replace them with others suitable for rotating application. Moreover we deduced that the position is also important for the proper operation of some components.

The cooling of the de excitation system was also very important, as it is installed in a large machine and the cooling air of the exciter is also used to cool down the HSBDS. The critical components were the transistor switch and the discharge resistor. Therefore the rated current of these components had been de rated according to the cooling air temperature.

Another important difference from our first prototype is the continuous operation of the system. The system should be able to operate continuously at rated excitation current and, in case of a short circuit, to operate with a higher current during a short time.



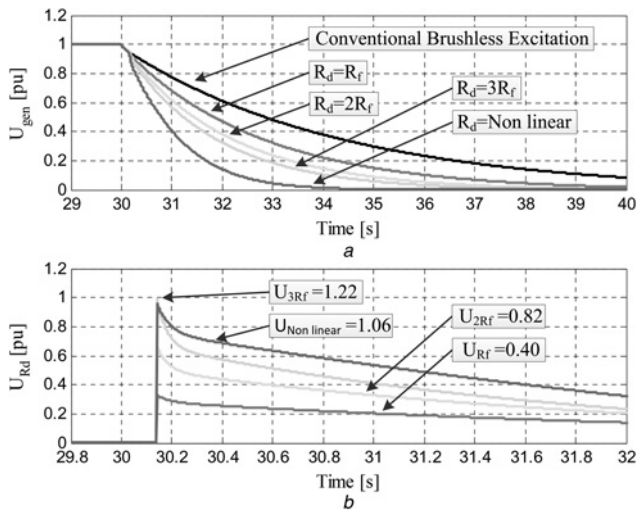
**Fig. 1** Simplified diagram of a brushless synchronous machine with a HSBDS

a During normal operation  
b During the de-excitation of the brushless synchronous machine

All of this has to be taken into consideration for the selection of the components.

Before starting the manufacture of the HSBDS for the power plant, computer simulations were performed to validate its design. These simulations were executed with the SimPowerSystems<sup>®</sup> of Matlab<sup>®</sup>, modelling the 20 MVA main generator and its complete excitation system, including the exciter, the static circuit breaker and the non linear discharge resistor.

The simulations were performed using the main generator and exciter ratings given in the Appendix. No load tests were performed with different values of discharge resistance to validate the optimal characteristics of the resistance as well as the linear and non linear resistor that were simulated.



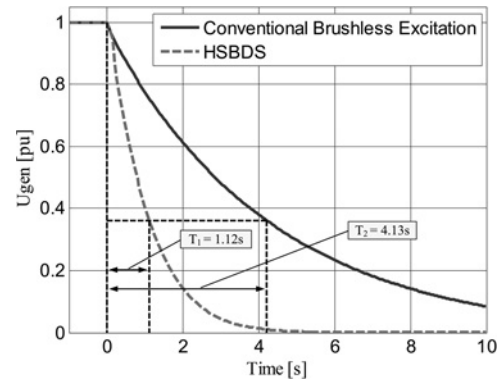
**Fig. 2** Simulation results of field breaker opening under no-load condition with different values of the discharge resistor

a Main generator voltage  
b Discharge resistor voltage

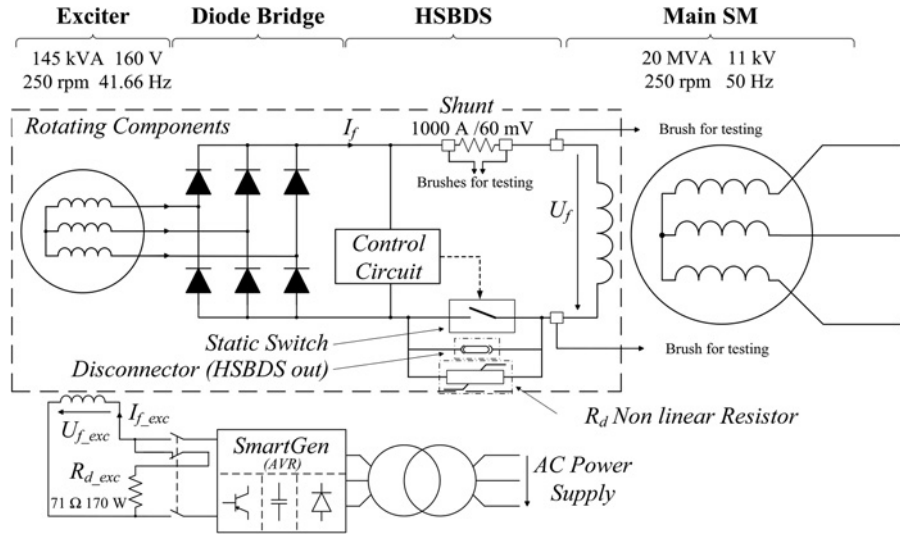
As expected, if the value of the discharge resistance increases, the de excitation time decreases remarkably (Fig. 2a), but the overvoltage in the field winding value increases (Fig. 2b).

Fig. 2a shows the main generator voltage response under de excitation from the rated voltage. The de excitation time, using the non linear discharge resistor selected, is reduced from 4.13 to 1.12 s, that is, 3.68 times, as shown in Fig. 3.

It is important to highlight that the non linear resistor decreases the de excitation time significantly. In addition, it produces smaller overvoltage in the semiconductor than the highest value of the linear discharge resistor simulated. In other words, the non linear resistor (with the same characteristics as the one installed in the real group) notably improves the HSBDS performance compared with a linear resistor, which produces a higher rotor overvoltage. This type of resistor is installed in some generators with static excitation system, but it was employed in this de excitation system for the first time.



**Fig. 3** Results of the simulation of the main generator stator voltage under conventional de-excitation and with the HSBDS after opening the field breaker under no-load condition



**Fig. 4** Simplified scheme of the excitation system of a hydro power plant of 20 MVA where the HSBDS was installed

The non linear resistor selected does not produce an overvoltage higher than the rated voltage of the main generator rotor, so this avoids endangering insulation of the main generator.

#### 4 Commissioning of the HSBDS in a 20 MVA brushless generator of a hydro power plant

The described system was installed experimentally in the hydro generator of a power plant where the original excitation system with a DC exciter was changed and substituted by a brushless exciter with a HSBDS.

The excitation scheme installed is based on the HSBDS with an AVR Smartgen type, as shown in Fig. 4. The control circuit measures the voltage of the diodes bridge, hence when the voltage is inverted, the transistor switch is turned off and the non linear discharge resistor ( $R_d$ ) is connected. An exciter discharge resistor ( $R_{d\_exc}$ ) was installed inside the exciter cabinet to demagnetise the exciter.

It is important to note that this installation has some particularities, as it is the first commercially built prototype of a HSBDS, which makes it possible to take some of the measurements presented in this paper. Two slip rings were installed that enable the measurement of the rotor current ( $I_f$ ) using a shunt of 1000 A/60

mV and a converter; another two brushes make it possible to measure the rotor voltage ( $U_f$ ). The other particularity of this machine is the possibility of taking the HSBDS out of service using a copper strip, named a 'disconnecter,' that bypasses the static circuit breaker, so that the excitation system can act as a conventional brushless machine (Fig. 5).

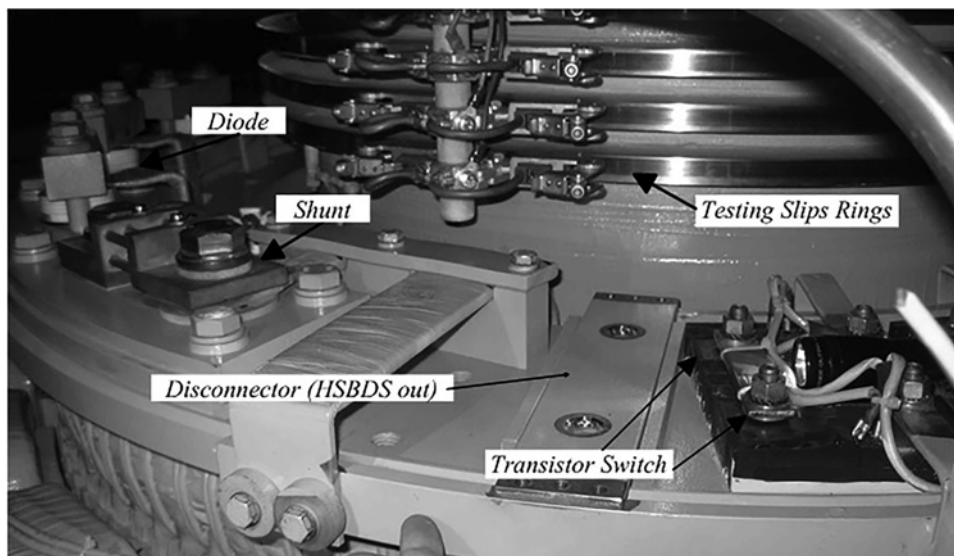
The main characteristics of the generator and the exciter are detailed in Tables 1 and 2, respectively (see Appendix).

The implemented system was installed in the upper part of the exciter. Several commercial semiconductor switches were used as the transistor switch. To reach a higher block voltage and higher current capacity, combinations of series and parallel connections were carried out.

The discharge resistor used is a non linear resistor [9] of SiC (Fig. 6a) that improves the response compared with a linear resistor. Fig. 6b shows the curve of one disk of the non linear resistor. The complete resistor is composed of 18 disks in parallel, obtaining a rated current of 900 A ( $C = 58 \Omega$ ,  $\beta = 0.5$  per disk).

##### 4.1 Results under no-load conditions

The results obtained during the commissioning are similar to those obtained by the computer simulations. It was also verified that the



**Fig. 5** HSBDS in a real 20 MVA generator; upper part of the exciter where the different components are installed



HSBDS operates properly in a real hydro power plant installed in a large generator with brushless excitation. The obtained results are the comparison between de excitation with a HSBDS and a conventional brushless exciter. The conventional brushless exciter operation was achieved by the disconnecter.

In Fig. 7a, the evolution of the main generator voltage during the de excitation is shown, where the de excitation time with the HSBDS ( $T_1$ ) is 1.054 s and the conventional de excitation time ( $T_2$ ) is 3.963 s. It can be observed that the de excitation time constant is dramatically reduced, four times, from 3.963 to 1.054 s. If these results are compared with the results obtained in the computer simulations (Fig. 3; 4.130 and 1.120 s), it can be clearly observed that the de excitation times are very close. Hence, it can be concluded that the computer simulation model is appropriate.

Fig. 7b shows the comparison between the rotor current with and without the HSBDS. The evolution of the current can be observed, responding in both cases to an inductive behaviour, but it is much faster with the HSBDS.

It is important to remark that at the moment of de excitation the rotor voltage is inverted, producing an overvoltage. Likewise, the overvoltage in the non linear resistor has the same value as the overvoltage in the main generator field winding. The overvoltage in the resistor depends largely on the curve of the non linear resistor selected. The comparison between the registered voltage in de excitation with and without a HSBDS is shown in Fig. 8a.

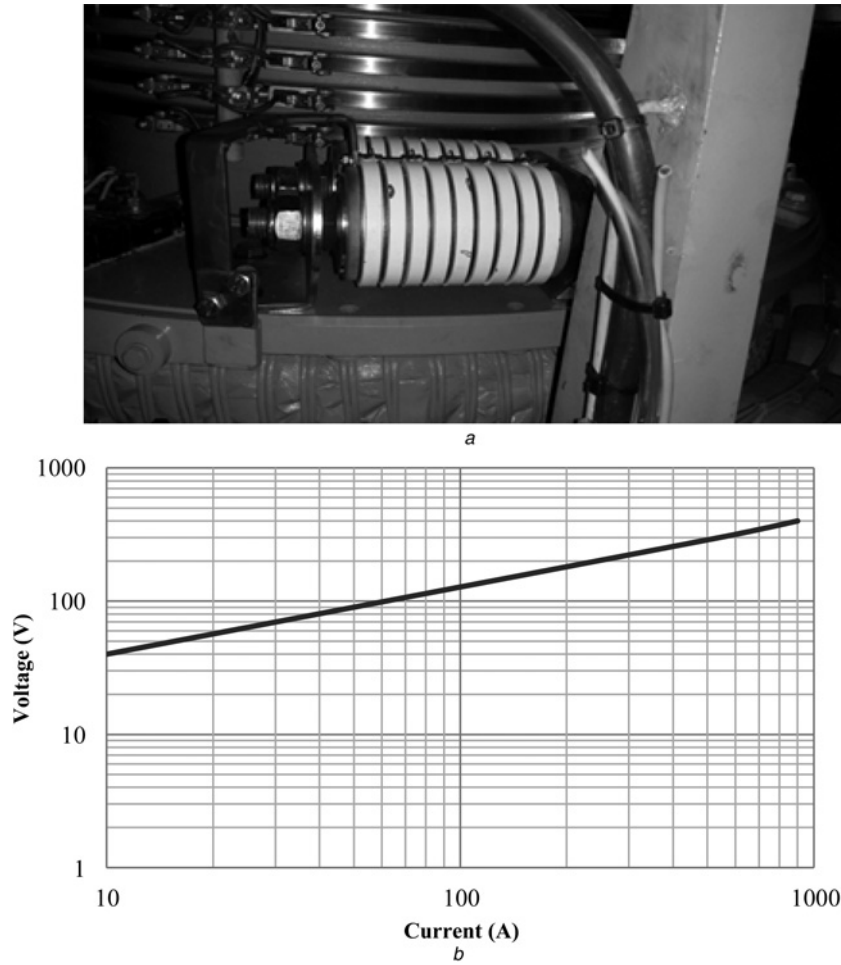
In addition, as described previously, a discharge resistor of the exciter ( $R_{d\_exc}$ ) was installed. This resistor is inserted in the exciter field winding circuit when the field breaker is open, producing similar overvoltage in both cases, as expected (Fig. 8b).

## 4.2 Results under load conditions

To test the HSBDS under load conditions, the generator was synchronised to the line. In this way, the field current can be increased. The transistor switch was tested under high field current conditions. Unfortunately, during the tests it was not possible to produce a trip of the generator and open the field breaker and the generator breaker at the same time, to check the HSBDS during de excitation with high field current. We were only allowed to stop the generator using the normal stop sequence; that is, the generator circuit breaker was open and 0.8 s later the field breaker was opened by the control system. As an example, a generator trip at 0.15 pu active power when the generating reactive power was 0.34 pu is presented. In Fig. 9 the evolution of the active and reactive power is shown. As expected, the active and reactive power drop to zero just before the generator breaker is opened.

Fig. 10a shows the evolution of the main generator voltage during a normal stop sequence. Fig. 10b shows the field winding current evolution during the de excitation, when it had a high initial value. It can be observed, just after the generator breaker opening, that the generator voltage suddenly increased and the field current was reduced by the automatic voltage regulator, to maintain the rated voltage at the machine terminals. When the field breaker is open the field current and the generator voltage are diminished by the HSBDS more rapidly by inserting the discharge resistor.

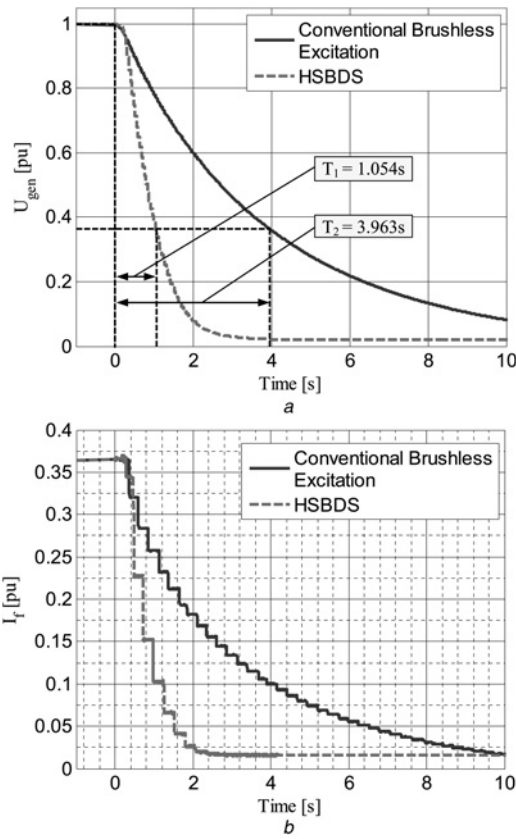
Finally, Fig. 11 shows the rotor voltage during the normal stop sequence. It can be observed that the voltage registered in the rotor is similar to de excitation under no load conditions, thanks to the non linear characteristic of the discharge resistor. The maximum overvoltage produced by the resistor has been limited to a value



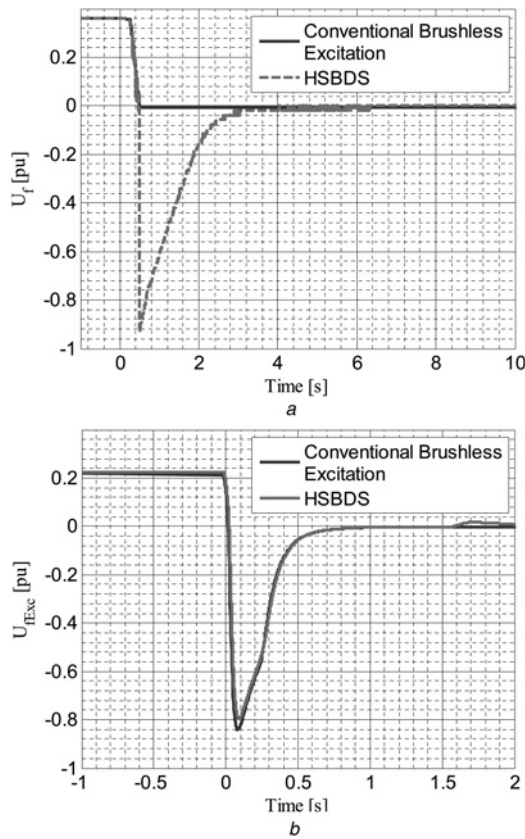
**Fig. 6** Discharge resistor used is a non-linear resistor

a HSBDS: non-linear discharge resistor mounted in the rotor

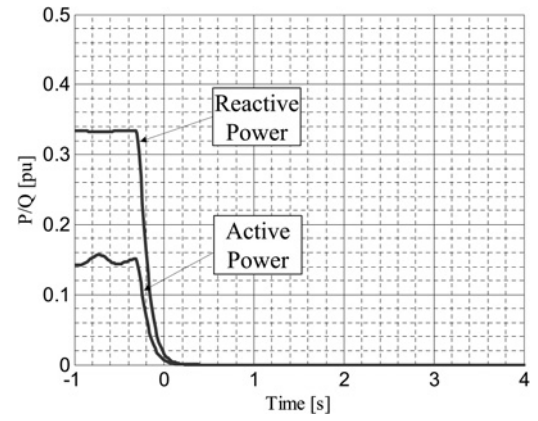
b HSBDS: non-linear discharge resistor characteristics (of one disk)



**Fig. 7** Comparison of the response under no-load de-excitation  
a Voltage in the main generator stator  
b Current in the main generator rotor



**Fig. 8** Comparison of the response under no-load de-excitation  
a Voltage in the field winding of the main generator  
b Voltage in the field winding of the exciter

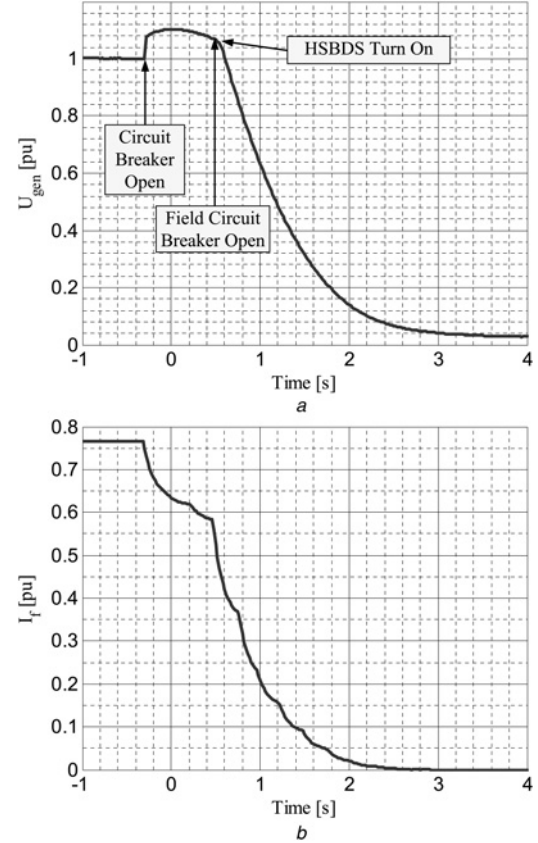


**Fig. 9** Evolution of the active and reactive power during a normal stop sequence

near to the rated rotor voltage of the main winding with the purpose of not endangering the insulation. Furthermore, the simulations also validated that with this level of voltage the field is dissipated in a reasonable time.

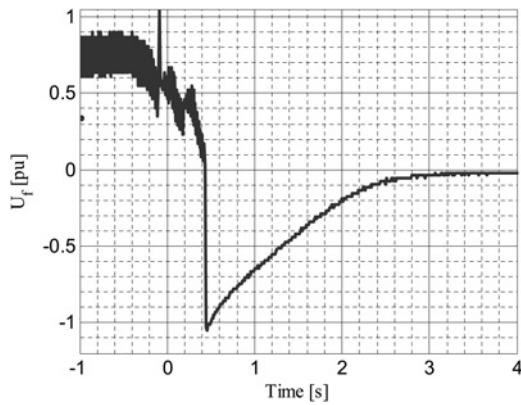
## 5 Conclusions

The HSBDS was designed, built, commissioned and tested in a 20 MVA commercial hydro generator. Good results were achieved under no load and load conditions, which validated operation of the HSBDS in large power synchronous generators. This 20 MVA hydro generator has been in commercial operation with the HSBDS for one year.



**Fig. 10** Normal stop sequence

a Voltage in stator of the main generator  
b Current in the field winding of the main generator



**Fig. 11** Overvoltage produced by the HSBDS in the main generator field winding during normal stop sequence de-excitation

Another remarkable improvement in comparison with the previous tests of the HSBDS in the laboratory is the use of a non linear discharge resistor, which notably improves the dynamic de excitation response compared with the use of a linear resistor. On the other hand, a standard non linear resistor was tested under rotating conditions without problems.

Among the results obtained during the commissioning, the de excitation under no load conditions is notable. The use of the new de excitation system allows a fourfold decrease of the no load de excitation time constant, keeping the maximum rotor voltage during the de excitation under its rated value.

## 6 Acknowledgments

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## 8 Appendix

This appendix presents the power plant data. The main generator and the exciter ratings are given in Tables 1 and 2, respectively.

**Table 1** Main generator ratings

Sécheron (Geneva/Switzerland) 1962	Type S24 360 145
rated apparent power	20 MVA
rated voltage (±5%)	11 kV
frequency	50 Hz
rated speed	250 rpm
rated power factor	0.85
rated excitation current	652 A
rated excitation voltage	210 V
no load excitation current	325 A
no load excitation voltage	104 V
reactance ( $X_d/X'_d/X''_d/X_q/X'_q/X''_q$ )	133/35.5/22.4/83.5/19.8%
time constants ( $T_d/T'_d/T''_d$ )	0.965/0.035/0.030 s

**Table 2** Exciter ratings

Alstom power (Bilbao/Spain) 2013	Type WE 11320 20/24
rated apparent power	145 kVA
rated voltage	160 V
frequency	41.66 Hz
rated speed	250 rpm
rated power factor	0.96
rated excitation current	8.3 A
rated excitation voltage	118.9 V
no load excitation current	4.3 A
no load excitation voltage	61.6 V
reactance ( $X_d/X'_d/X''_d/X_q/X'_q/X''_q$ )	113/28.1/26.6/71.4/58.6%
time constants ( $T_d/T'_d/T''_d$ )	0.285/0.024/0.031 s